

Comparison of minimum energy consumption indicators for electric motors powered directly from the mains at part loads

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Abstract. The article presents a comparison of minimum energy consumption indicators for motors powered directly from the mains at part load conditions. The energy characteristics of induction motors and line-start permanent magnet synchronous motors of different energy efficiency classes are compared. As an example, the calculations of proposed energy consumption indicators are provided for the throttle-controlled 2.2 kW pump unit with variable flow-time profile. It is shown that if a motor is used mostly at part load conditions and was chosen by its energy efficiency class only, minimum energy consumption might not be achieved. Universal average efficiency indicator is suggested for motors running at variable loads with output power much lower than the rated power. The comparison shows that the proposed average efficiency does not depend on a specific application or load profile and describes the motor energy consumption enough for practical goals. Thus, this indicator can be used for fast evaluation and selection of a motor by the lowest energy consumption criterion, especially without detailed information about load profile. Calculation of this indicator requires only motor efficiency data per 4 points 25, 50, 75, 100% of rated load.

1. Introduction

A significant number of electric motors in the world currently run without speed control. For instance, the share of VSDs (variable speed drives) according to the European Commission data [1] is about 30% for Germany and about 20% for Switzerland according to the study described in [2]. The energy efficiency class (IE) of the motor powered directly from the mains is assigned by the efficiency at rated output in accordance with IEC 60034-30-1 [3]. At the same time, the efficiency values for part loads are not defined by the standard [3].

However, the electric motor running mode is far from the rated mode in many applications. This is typical for HVAC (heating, ventilation, air conditioning) and water supply. E.g. a pump unit's motor with a variable load depending on water consumption may run at part loads for a long time. Whereas a lower-power motor can't be used as peak consumption has to be provided. For example, the typical circulation pump flow-time profile defined by [4] and [5] is divided into 4 modes: a pump runs for 44% of its working time with of 25% of the rated flow; 35% of the time with 50% of the flow rate; 15% of the time with 75% of the flow rate; and time in the rated mode does not exceed 6%. The similar load profile can be typical for conveyors and hoisting mechanisms where the motor's load depends on the mass transported, in crushers and other materials processing equipment where the motor load depends on the quantity and properties of the material processed.



In many cases motors are overrated. For example, in [6] it is estimated that only 20% of the pump drive motors in operation are running at their rated mode. Many articles are focused on comparison of power consumption of pump systems and other centrifugal mechanisms using various motor's types like IMs (induction motors), PMSMs (permanent magnet synchronous motors), SynRMs (synchronous reluctance motors) [7, 8, 9, 10, 11, 12, 13, 14]. However, all these articles consider pumping systems with VSDs. For pump units powered directly from the mains, the issue of efficiency is far less reviewed for different motor. Thus, the main purpose of the article is to compare the indicators of minimum energy consumption for selection of motors running mostly at loads below the rated value. The article compares the motors' efficiency dependences of the load. Data were analyzed for 8 different 4-pole 2.2 kW motors, namely: three LSPMSMs (line-start PMSMs) of IE4-class [15], [16], [17]; two IMs of IE4-class [18] and [19]; and three IMs of IE3-class [18], [20] and [21]. Motor performance data are shown in table 1, where m is the index number of the motor.

Table 1. Efficiency of motors chosen [15-21].

m	Type of motor	Efficiency class	Efficiency (%) at the various loads			
			25 %	50 %.	75 %.	100%.
1	LSPMSM (SEW DRU J)	IE4	-	88.0	90.5	91.2
2	LSPMSM (SynchroVERT)	IE4	-	88.6	89.4	89.5
3	LSPMSM (WEG WQuattro)	IE4	77.0	86.0	89.0	90.2
4	IM (Siemens 1LE1004)	IE4	82.3	88.3	89.6	89.5
5	IM (WEG W22)	IE4	79.3	88.5	89.5	89.5
6	IM (Siemens 1LE1003)	IE3	80.4	86.4	87.3	86.7
7	IM (WEG W21)	IE3	80.6	86.5	87.0	87.0
8	IM (ABB M3BP)	IE3	-	85.1	86.9	86.7

Figure 1 shows the interpolated efficiency curves for all electric motors on the same coordinate axes and data from Table 1. The loss values were calculated for each motor according to the efficiency values from table 1, then their polynomial interpolation was performed, then the efficiency values were determined over the entire range of 0 to 100%.

The data in table 1 and figure 1 show that some IE4-motors at part loads have the efficiency lower than that of IE3-motors at same loads below the rated load. The most typical example is the LSPMSM no.3, which has the rated efficiency greater than that of all the IMs considered. However, its efficiency is 86% at 50% load and 77% at 25% load. At the same time, the IE3-class IMs no.6 & no.7 show the efficiency of 86.4% and 86.5% accordingly at 50% load and 80.4% and 80.6% at 25% load, which is much higher than that of LSPMSM no.3. It should be noted that in the LSPMSMs no.1 to no.3 are used expensive rare earth magnets, and its manufacturing leads to the high impact on the environment [22]. According to the author's estimation, the LSPMSMs have the price about 1.27–1.37 times higher than that of IE3-class IMs. Thus, for some applications like variable-flow pumps, selection of electric motor based only on its IE-class might not give the minimum energy consumption, as was shown in [23]. The curves in figure 1 show a general view of the efficiencies compared, but they give no specific numerical indicator according to which one of the electric motors can be chosen for a specific application.

2. Methods

Let's consider possible methods for determining the indicator of motor energy consumption at part load conditions. Usage of the rated motor efficiency $\eta_{\text{nom},m}$ for m th motor was taken as the method A. By the method B, the average efficiency $\eta_{\text{avg.int},m}$ is calculated for the m th motor in the range $l_{\text{min}} \dots l_{\text{nom}}$ by an interpolated efficiency curve $\eta_{\text{int},m}(l)$ for the m th motor, assuming that a long run at a load less than 25% is unlikely, so $l_{\text{min}} = 25\%$ and $l_{\text{nom}} = 100\%$.

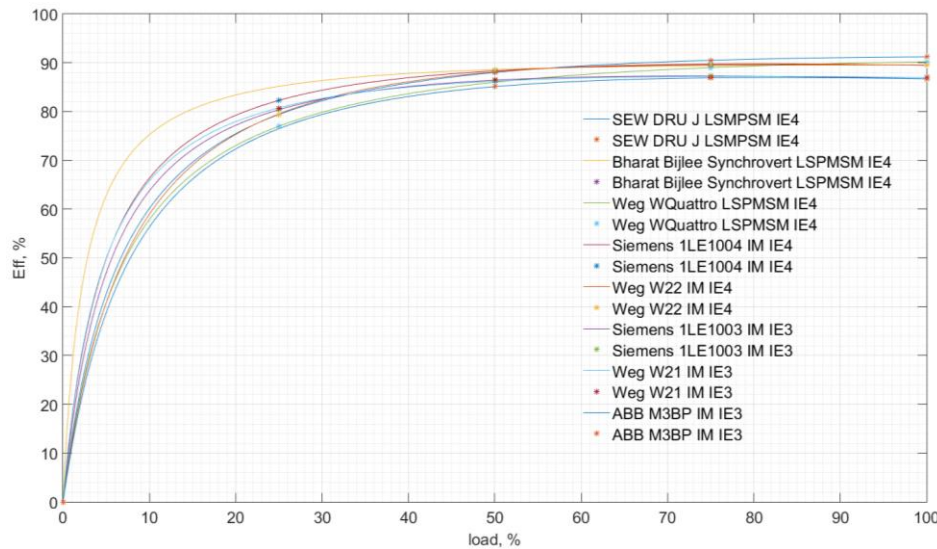


Figure 1.
Interpolated
curves of motors'
efficiencies and
the initial points.

$$\eta_{\text{avg.int.m}} = \frac{1}{(l_{\text{nom}} - l_{\text{min}})} \int_{l_{\text{min}}}^{l_{\text{nom}}} \eta_{\text{int.m}}(l) dl \quad (1)$$

By the method C, the average efficiency $\eta_{\text{avg.m}}$ was calculated in load points i : 25, 50, 75, 100% as indicated in table 1 for m th motor. If the efficiency at 25% point doesn't specified by the manufacturer, this value was previously calculated using interpolated curves.

$$\eta_{\text{avg.m}} = \frac{1}{4} \sum_{i=1}^4 \eta_{i.m} \quad (2)$$

Method D is a detailed energy consumption calculation for a motor in a specific operating cycle in a specific application. For example, energy efficiency of circulation pumps working mainly with variable flow is evaluated in accordance with the [4]. In the [4], the previously described flow-time profile is used as a typical pump load profile. The efficiency indicator in [4] is the energy efficiency index (EEI), which is a ratio of the average-weighted electric power consumed by the pump over the operating cycle to the electric power of the reference pump system. Thus, the lower EEI values correspond to the higher energy efficiency of the pump unit. According to [5], the EEI is the most appropriate indicator for evaluating the energy efficiency of pumping systems with variable flow rates for various purposes, unlike the minimum efficiency index (MEI), which is defined in [24] and is based on a limited range of operating points (75 to 110% of the flow rate) [5].

According to [25] and [26], the EEI calculation requires: interpolated electric motors' efficiency curves for calculating electric energy consumption at flows according to a load profile given; pump parameters: Q - H characteristic, pump efficiency dependence of flow; a number of reference parameters: efficiency of the reference motor, the minimum required efficiency of the reference pump at the best efficiency point (BEP), depending on the table coefficient C , determined by the pump type, the nominal rotational speed of the pump n and its efficiency, the flow rate Q_{BEP} and the specific speed n_s , which depends on the head H_{BEP} and n . As shown in [23], the EEI explains the energy consumption of the pump unit more objectively than the energy efficiency class of the motor, which depends only on the rated efficiency. Also, [23] describes a method for calculating the energy consumption of a pump unit, which does not require reference parameters and provide cost savings.

In [23], the calculation of the energy efficiency of a pump unit with the same motors as in this article, with a typical load profile [4], i.e. a comparative analysis is performed for energy consumption of LSPMSMs and IMs powered directly from the mains in the electric drive of a centrifugal pump with throttle control. We use the results of the cost savings calculation from [23] as an accurate

criterion for comparison the energy consumption of electric motors of a pumping unit with variable flow, which is more convenient for comparison with indicators for the methods A, B, C than EEI, since a higher cost savings values correspond to a lower energy consumption, as well as efficiency.

The indicators calculating results for all methods are shown in table 2 and figure 2.

Table 2. Energy consumption indicators for motors chosen.

<i>m</i>	Type of motor	Class	Method A $\eta_{\text{nom},m}$, %	Method B $\eta_{\text{avg.int},m}$, %	Method C $\eta_{\text{avg},m}$, %	Method D Cost savings, €
1	LSPMSM (SEW DRU J)	IE4	91.2 ^a	88.3	87.3	73,8
2	LSPMSM (SynchroVERT)	IE4	89.5	88.6 ^a	88.2 ^a	93,6 ^a
3	LSPMSM (WEG WQuattro)	IE4	90.2	86.6	85.6	24,6
4	IM (Siemens 1LE1004)	IE4	89.5	88.2	87.4	83,8
5	IM (WEG W22)	IE4	89.5	87.9	86.7	74,8
6	IM (Siemens 1LE1003)	IE3	86.7 ^b	86.1	85.2	36,6
7	IM (WEG W21)	IE3	87.0	86.0	85.3	32,5
8	IM (ABB M3BP)	IE3	86.7 ^b	85.0 ^b	83.6 ^b	0 ^b

^aThe best value for the method. ^bThe worst value for the method.

3. Results and discussion

Table 2 and figure 2 show that the energy efficiency assessment of motors by the methods B and C are almost identical and mostly meet the indicator by the method D. The motor no.2 has the best average efficiency by both methods B and C, and electric motor no.7 has the worst values. The similar result is shown by the most accurate method D. Thus, an average efficiency classifies the motor energy consumption at low loads and at least can be used for fast evaluation and selection of a motor by the lowest energy consumption criterion, especially without detailed load profile information. In this case, the methods B and C give a better result than selecting a motor by its rated efficiency, according to the method A. It should be noted that according to IEC 60034-30-2 [27] the efficiency values for variable speed motors are defined for seven load modes other than the rated one. The draft of IEC 60034-30-2 [28] proposed to calculate the overall efficiency for variable speed motors of pumps and fans (drives with a quadratic load-speed dependence) as an average-weighted value of efficiency at reduced speeds and loads. In [29, 30], an approach to the design of an electric motor is described, which allows to maximize the overall efficiency calculated according to the draft version of the standard [28], not only the rated efficiency.

The method B disadvantage is the necessity of the interpolation of efficiency dependence of the load. In this case, some interpolation error may be added. For example, the motor no.2 interpolated efficiency curve looks better relative to other motors in the range of 0 to 35% of the load. As the motor manufacturer does not specify the efficiency at 25% load in the catalog, there are only 3 initial points for interpolation. On the one hand, as shown in [13] and [31], the motor losses dependence of load is well described by a second-order polynomial, coefficients of which can be easily obtained by the 3 initial data points. On the other hand, this motor has some minor efficiency differences, and therefore in the values of losses, at known points 50, 75, 100% of the load. Even with a known point (0, 0) on the efficiency curve, this can lead to an interpolation error. Thus, the resulting indicator for the method B may not be completely reliable for motors for which the efficiency is unknown at a load of 25% and having a flat efficiency curve in the range of 50 to 100% of the load.

The general disadvantage of the methods B and C is that the indicator does not describe a specific running time in each mode, i.e. it assumes the same relative running time in each mode. Method D does not have this disadvantage. Method D, although being the most accurate of the methods proposed, assumes usage of known load profile.

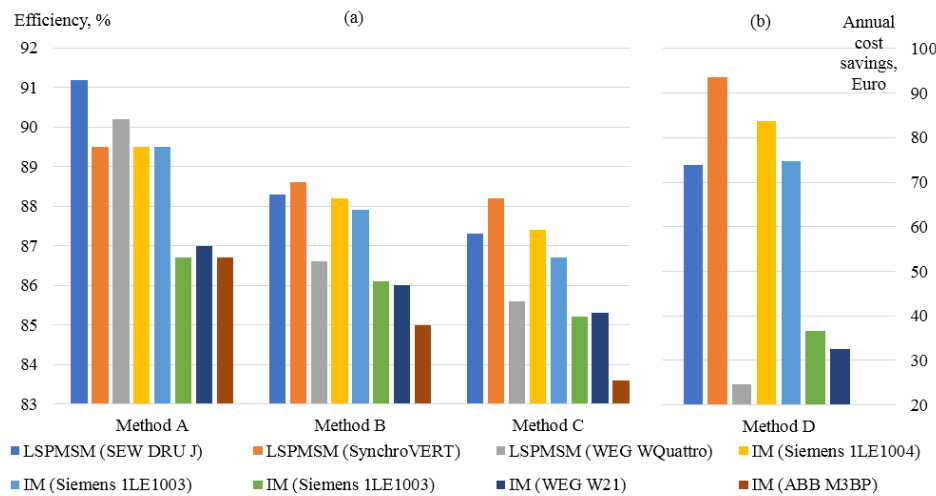


Figure 2. Energy consumption indicators: (a) – methods A, B, C; (b) – method D.

The profile used in [4] is the result of statistical processing but the load profile of a real pump may be much different from it. In this case, it is necessary to make the calculation according to the method described in [23], using experimental or calculated load profile. Likewise, another mechanism requires a defined load profile to perform this calculation. However, not many mechanisms have standard load profiles approved as a standard, also the actual operating conditions of specific mechanisms may differ from the standard profile.

4. Conclusions

With a known load profile, the most accurate result can be obtained using method D, i.e. a detailed calculation of energy consumption in each mode with further cost savings calculation according to [23] or the EEI according to [4, 25, 26]. The average efficiency calculated using the method C does not depend with a specific application or load profile and describes the motor energy consumption enough for practical goals. This method requires only motor efficiency data per 4 points (25, 50, 75, 100% loads) for calculation, i.e. it does not have the disadvantages that are present when calculating EEI or cost savings, as well as when selecting a motor by IE class (by rated efficiency). We consider it relevant to use the average efficiency not only for VSD motors, which was proposed in [28], but unfortunately was not approved in the final version of the standard [27], but also for motors powered directly from the mains. For such motors, at least, both the rated efficiency and the efficiency values at reduced loads are to be considered, according to the approach proposed in [27].

It should also be noted that applications with variable loads require motors with a flat efficiency curve (ideally in the range of 25 to 100% of the load). Then the specific load profile will not be so important, and in this case the motor efficiency will be conveniently classified by the average efficiency calculated by the method C. The consumer will be able to focus either on the rated efficiency for selection of the motor running close to the rated output, or on the average efficiency for selection of the motor running under various loads, especially if there is no detailed information about load profile. The average efficiency could also be used to assign energy efficiency classes to motors powered directly from the mains and intended for running in a wide range of loads, along with the approach already available in the standard [3], which is more suitable for electric motors running mainly close to the rated mode.

References

- [1] Almeida A, Ferreira F J, Fong J and Fonseca P 2008 EuP Lot 11 Motors, Final report to the EC.
- [2] Phillips R and Tieben R 2017 *Proc. of Energy Efficiency in Motor Driven Systems (EEMODS)* (Rome) pp 53-60.
- [3] Rotating electrical machines - Part 30-1: Efficiency classes of line operated AC motors (IE code). IEC 60034-30-1/ Ed. 1; IEC: 2014-03.

- [4] European Commission Regulation (EC) No. 640/2009 Implementing Directive 2005/32/ EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Electric Motors amended by Commission Regulation (EU) No 4/2014.
- [5] Stoffel B 2015 *Assessing the Energy Efficiency of Pumps and Pump Units. Background and Methodology* (Amsterdam, The Netherlands Elsevier).
- [6] Glover A and Lukaszczyk M 2005 *World Pumps* **466** pp 36–38.
- [7] Ahonen T, Orozco S M, Ahola J and Tolvanen J 2016 *18th European Conf. on Power Electronics and Applications (EPE)* (Karlsruhe) pp 1-9.
- [8] Van Rhyn P and Pretorius J H C 2015 *IEEE 5th Int. Conf. on Power Engineering, Energy and Electrical Drives (POWERENG)* (Riga) pp 497-502.
- [9] Brinner T R, McCoy R H and Kopecky T 2014 *IEEE Trans. on Ind. Appl.* **50** **1** pp 174-181
- [10] Kazakbaev V, Prakht V, Dmitrievskii V, Ibrahim M N, Oshurbekov S and Sarapulov S 2019 *Energies* **12** 1144.
- [11] Safin N, Kazakbaev V, Prakht V and Dmitrievskii V 2018 *25th Int. Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED)* (Moscow) pp 1-5.
- [12] Kazakbaev V M, Prakht V A and Dmitrievskii V A 2017 *Russ. Electr. Eng.* **88** 233–238.
- [13] Safin N, Kazakbaev V, Prakht V, Dmitrievskii V and Sarapulov S 2018 *25th Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED)* (Moscow) pp 1-5
- [14] Kazakbaev V, Prakht V, Dmitrievskii V, Sarapulov S and Askerov D 2017 *Int. Siberian Conf. on Control and Communications (SIBCON)* (Astana) pp 1-6.
- [15] https://www.bharatbijlee.com/media/14228/synchrovert_catalogue.pdf (accessed on 1 May 2020)
- [16] <https://www.weg.net/catalog/weg/RU/en/Electric-Motors/Special-Application-Motors/Permanent-Magnet-Motors/Line-Start-PM-Motors/Wquattro-2-2-kW-4P-100L-3Ph-230-400-V-50-Hz-IC411---TEFC---B3T/p/13009386> (accessed on 1 June 2020).
- [17] <https://download.sew-eurodrive.com/download/pdf/21343799.pdf> (accessed on 1 June 2020).
- [18] Catalog Siemens D81.1 Simotics GP, SD, XP, DP low-voltage motors, 05/2018.
- [19] <https://www.weg.net/catalog/weg/MV/en/Electric-Motors/Low-Voltage-NEMA-Motors/General-Purpose-ODP-TEFC/Cast-Iron-TEFC-General-Purpose/W22-Super-Premium-Efficiency/W22-Super-Premium-Efficiency-3-HP-4P-182-4T-3Ph-208-230-460-380-V-60-Hz-IC411---TEFC---Foot-mounted/p/12792146> (accessed on 1 June 2020).
- [20] <https://www.weg.net/catalog/weg/RU/en/Electric-Motors/Low-Voltage-IEC-Motors/General-Purpose-ODP-TEFC/Aluminum-TEFC-General-Purpose/Aluminium-TEFC-General-Purpose/Multimounting-IE3/Multimounting-IE3-2-2-kW-4P-100L-3Ph-220-240-380-415-460-V-50-Hz-IC411---TEFC---B3T/p/12397774> (accessed on 1 June 2020).
- [21] Catalog ABB - Low Voltage General Performance motors, June 2018.
- [22] *Rare Earth Industry* 2016 ed W Ismar Borges de Lima and Walter Leal Filho (Elsevier).
- [23] Goman V, Oshurbekov S, Kazakbaev V, Prakht V and Dmitrievskii V 2019 *Appl. Sci.* **9** 5295
- [24] Commission Regulation No 547/2012 Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Water Pumps.
- [25] Extended product approach for pumps. A Europump Guide 2014 (Europump).
- [26] Lang S, Ludwig G, Pelz P F, Stoffel B 2013 *Proc. of Energy Efficiency in Motor Driven Systems (EEMODS)* (Rio de Janeiro) pp 385-397.
- [27] Rotating Electrical Machines—Part 30-2: Efficiency Classes of Variable Speed AC Motors (IE-Code); IEC TS 60034-30-2:2016; IEC: Geneva, Switzerland, 2016.
- [28] Rotating Electrical Machines—Part 30-2: Efficiency Classes of Variable Speed AC Motors (IE-Code); Document 2/1709/NP; Standard draft; IEC: Geneva, Switzerland, 2013.
- [29] Dmitrievskii V, Prakht V and Kazakbaev V 2019 *IEEE Trans. on Ind. Appl.* **55** **5** pp 4676- 84.
- [30] Dmitrievskii V A, Prakht V A and Kazakbaev V M 2018 *XIII Int. Conf. on Electrical Machines (ICEM)* (Alexandroupoli) pp 1015-20.
- [31] Ferreira F, Almeida A 2016 *Int. Conf. on Electrical Machines (ICEM)* (Lausanne), pp 2775-83.